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The impact of urbanisation on energy consumption: A 30-year review in China

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A R T I C L E I N F O

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A B S T R A C T

Cities are a major battlefield in humanity's struggle to save energy and combat climate change. In China, the cities have surpassed the industrial sector and become the largest consumers of energy. This paper explores how the process of urbanisation affected energy use in China 1980–2010. The results of the analyses show that for every 1% increase in the urban population relative to the total population, national energy consumption rose 1.4%, while industrialisation was not significantly associated with the growth of energy use during this period. Urbanisation has increased energy consumption along three main pathways: urban spatial expansion, where urban sprawl has increased energy consumption in new buildings and the transport sector; urban motorisation, which induces energy-intensive transportation; and the rising quality of energy-intensive lifestyles. Urban households consume 50% more energy than rural households per capita, which indicates that continued urbanisation in China will promote the growth of national energy consumption. Urban policies designed to encourage compact urban growth, green buildings and new energy vehicles could thus play a vital role in saving energy. Undoubtedly, the changes in lifestyle and growth of a consumption society and e-Society will bring new challenges to energy-saving policies and climate change mitigation initiatives in China.

1. Introduction

Cities have become a major focus in the field of global climate change. This is not only because cities are one of the main contributors to fossil-fuel energy consumption and greenhouse gas (GHG) emissions in the world, but also because city policies are vital for the mitigation of and adaptations required in relation to climate change (Bulkeley, 2013). It has been reported that cities consume the great majority – between 60 and 80% – of energy production worldwide and account for roughly an equivalent share of global CO_2 emissions (OECD, 2010).

Cities contribute to climate change in three main ways: through direct emissions of GHGs that occur within city boundaries; through the GHG emissions that originate outside the city boundaries but are embodied in civil infrastructure and urban energy consumption; and through city-induced changes to the earth's atmospheric chemistry and surface albedo. In particular, energy use in cities is a key issue for GHG emissions. In OECD cities, GHG are increasingly driven less by industrial activities and more by the energy required for lighting, heating and cooling, as well as electronics and transport mobility (IEA, 2009).

Recently, the relationship between urbanisation and energy use has been attracting the increasing interest of researchers and politicians (Salim and Shafiei, 2014; Pachauri and Jiang, 2008; Liu, 2009). Growing urbanisation will lead to a significant increase in

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energy use and CO_2 emissions, particularly in non-OECD countries in Asia and Africa, where urban energy use is shifting from CO_2-neutral energy sources such as biomass and waste to CO_2-intensive energy sources (OECD, 2010). In practice, policymakers are often confused about how to manage urban growth to reduce the impact of urbanisation processes on energy use. Although many researchers have discussed the issue, a consensus has yet to be reached, especially since the issue is viewed within different contexts (Sadorsky, 2014; Pachauri and Jiang, 2008; Poumanyvong et al., 2012; Hossain, 2011).

In China, there has been rapid urbanisation since the 1980s, known as 'China's growth miracle' (Wu, 2004). During the period from 1978 to 2012, the country's urbanisation rate (the percentage of the total population that is considered urban) increased from 17.92% to 52.57%. The urban population increased by 10 million annually (China Statistical Bureau 2012) and 498 cities were newly recognised during the same period, many of which had begun as villages or small rural towns. China is thus shifting from a conventional agricultural society to an industrial and urban society (Deng et al., 2008; Lin, 2002). Such rapid urbanisation has caused problems for environmental protection and energy savings. Energy consumption grew from 410.1 million tonnes of oil equivalent (mtoe) in 1980 to 2735.2 mtoe in 2012 (China Energy Statistical Yearbook 2012). In the meantime, China has become the world's largest emitter of greenhouse gases, showing a vigorous growth from 1467 megatons in 1980 to 8287 megatons in 2010 (World Bank, 2015). A recent forecast by the International Energy Agency highlights this continuous growth, showing that energy consumption in China will reach 5500 mtoe – double the US level – and account for more than a quarter of the world's total energy consumption by 2040 (International Energy Agency, 2013). In China, 60% of this energy was consumed in cities, and energy consumed individually by the urban population is on average 1.3 times that consumed by the rural population (China Energy Statistical Yearbook 2012).

Petrol use and coal burning have caused a serious problems with public health. In China, more than one million people have died from air pollution created by road transport. Emissions from cars are the main source of PM2.5 and haze weather every year, which the central government and local authorities both consider the most important environmental problem; for example, road transport contributed > 30% of the total PM2.5 in Beijing, 21% in Tianjin and 26% in Guangzhou.

Reducing energy use and promoting green energy in cities has become a key mission at different levels of government in China. In 2009, the central government developed a national-level policy which aimed 'to build an environmentally friendly society and a resource-saving society'. According to the policy, protecting the environment, saving energy and reducing emissions are essential elements of urban development in China. Detailed institutional reforms to the existing governance organisation, laws and regulations were undertaken to implement this national policy. According to the latest National Energy Development Strategy, cities are the main battlefield for governments struggling to constrain the rapid growth in energy consumption. Many new sustainable strategies have been discussed and applied by local governments to decrease energy use in cities, including low-carbon cities, green cities and eco-cities.

China's cities provide researchers with a good case study of the relationship between urbanisation and energy use. While a large amount of literature has discussed the relationship between urbanisation and energy use at the national level (Jones, 1989; Parikh and Shukla, 1995; Lariviere and Lafrance, 1999; Ewing and Rong, 2008; Poumanyvong et al., 2012; Al-mulali et al., 2012; Hossain, 2011), consensus is still lacking. Moreover, most previous studies conducted at the national level have focused on identifying the relationship between energy consumption and urbanisation: few studies discuss how urbanisation affects energy consumption. Apart from total energy use, urbanisation and related changes in lifestyle could also affect the structure of energy use, but this issue is less discussed in the existing literature.

This paper aims to fill these research gaps by exploring the impact of urbanisation on energy use in China during the period 1980 to 2010. While some similar studies have been conducted on urbanisation and energy use in China (Dhakal, 2009; Liu, 2009; O'Neill et al., 2012; Poumanyvong and Kaneko, 2010a, 2010b; Zhang and Lin, 2012), several important questions still require further investigation. Firstly, how does urbanisation affect energy consumption in China? This remains to be addressed (Adams and Shachmurove, 2008). Secondly, which urban policies should be applied to change the course of urbanisation so that increasing energy demand is constrained and green energy use promoted in China? This paper intends to answer these two major questions.

The paper is organised as follows: Section 2 provides a comprehensive literature review on the dynamic relationship between urbanisation and energy consumption. Section 3 describes the trends in China's energy consumption during the rapid urbanisation period from 1980 to 2010, with a quantitative analysis of energy consumption and urbanisation also being presented. Section 4 discusses how urbanisation in China affects energy consumption, including the differences in energy consumption patterns between urban and rural areas. Section 5 will present a discussion and policy implications, while Section 6 will offer our conclusions.

2. Literature review and theoretical framework

The management of urbanisation and city growth may have important implications for energy-saving strategies (Ewing and Rong, 2008; Zhang and Zhao, 2016). The effectiveness and efficiency of urban management in terms of energy savings depends on the relationship between them. Many studies have examined this relationship, with most verifying that urbanisation is significantly correlated with energy consumption. For example, Jones (1989) found that, on a national level, a higher level of urbanisation was related to a higher level of energy use in 59 developing countries. This positive relationship was also confirmed by Parikh and Shukla (1995), who conducted a double logarithmic regression model of 78 developed and developing countries. One major reason for the link is that urbanisation causes a growth in the share of the urban population. Other studies found that urbanisation may increase energy efficiency; for example, Lariviere and Lafrance (1999) found that urbanisation led to lower per capita energy consumption in Canada, indicating that more urbanised areas have increased energy efficiency. Similar results have been reported by Ewing and Rong (2008) in the US.

It is possible that the relationship between urbanisation and energy use is nonlinear. Malenbaum (1978) argued that energy use

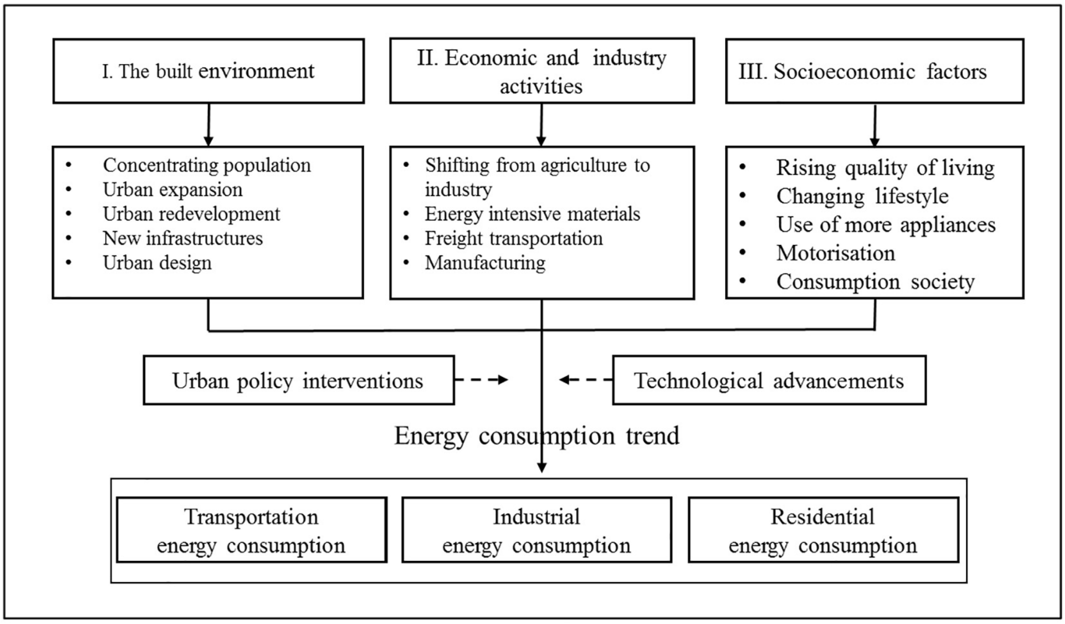

Fig. 1. The theoretical framework of the impact of urbanisation on energy consumption.
Source: the authors.

initially increased with rising average income and urbanisation, eventually reaching a plateau, after which energy consumption began to decline with further increases in average income and urbanisation. Lin and Ouyang (2014) found an inverted U-shaped relationship between energy demand and economic growth in the long term. Energy consumption increased as urbanisation increased in the early stage, then, after consumption reached a peak level, an increase in urbanisation was related to a decline of energy use. This was largely attributed to the enhancement of energy efficiency.

How urbanisation affects energy consumption is another important theme in the field. The theoretical relationship between urbanisation and energy consumption can be summarised, as shown in Fig. 1. Previous studies have framed discussions of the causes and processes linking urbanisation with energy use into three dimensions (Jones, 1989, 1991; Madlener and Sunak, 2011; Parikh and Shukla, 1995; Sadorsky, 2014). Firstly, different elements of urbanisation affect energy use in different ways. These elements include the built environment, economic and industrial activities, and socioeconomic factors. Urban expansion describes growth in the amount of construction and the operation of buildings, roads and facilities, which causes a massive increase in energy consumption. Urban sprawl, compared to a compact urban form, is often criticised because it causes extractive energy use by buildings, infrastructure and transport (Poumanyvong et al., 2012; Madlener and Sunak, 2011).

Secondly, urbanisation has complicated links with energy use due to the complexity of the process. Urbanisation includes economic processes, social processes, spatial processes and technological processes. In terms of economic processes, urbanisation means a shift from a less energy-intensive agricultural society to high energy-intensive urban society. Commercial and industrial manufacturing activities grow and agglomerate in cities, resulting in an increase in energy use (Jones, 1989, 1991). In particular, industrial production, which needs a more diverse and complex array of inputs and procedures, relies heavily on intensive and massive energy use (Sadorsky, 2014).

In addition, urbanisation promotes a concentration of economic activities, which leads to scale economies, thus reducing average energy costs per capita. The social process of urbanisation means a change from a rural lifestyle to an urban lifestyle. The growth in urban lifestyles is one major factor influencing individual energy consumption patterns (Sadorsky, 2014), as consumption of energy-intensive products increases (Jones, 1989, 1991). Compared with rural residents, urban inhabitants have a higher level of energy consumption due to their higher levels of social and economic activity, such as more travelling, long-distance commuting to work and increased car use (Heinonen and Junnila, 2011; Jones, 1989; Cai and Jiang, 2008).

Increasing motorised travel in cities leads to an increasing demand for transportation energy (Poumanyvong et al., 2012). In developing countries, urban residents also use more electrical appliances, such as air conditioners, refrigerators and lighting, than rural residents. In terms of technological processes, urbanisation is accompanied by technological advances which could improve energy efficiency (Ye et al., 2013).

Thirdly, urban policy interventions in relation to the urbanisation process could change the course of energy use (Malenbaum, 1978; Bernardini and Galli, 1993). Urban policies (e.g. compact city policy, new urbanism, smart growth and transit city strategies) play an important role in saving energy (Poumanyvong et al., 2012). Furthermore, more urbanised areas usually have better regulations and governance to implement energy-saving technologies and standards (Madlener and Sunak, 2011).

It should be also recognised that the relationship between urbanisation and energy consumption is contextual. Al-mulali et al. (2012) found a bi-directional long-running relationship between urbanisation and energy consumption which was significantly

affected by the level of national development. Poumanyvong et al. (2012) found that urbanisation reduced energy consumption in low-income countries, while prompting higher energy consumption in high-income countries. Poumanyvong et al. (2012) found that urbanisation increased transportation energy consumption, and that the relationship was stronger in high-income countries than low-income countries. Hossain (2011) studied nine developing countries and found a negative relationship between urbanisation and energy consumption. One of the major reasons for this result was that these countries were in the early stages of urbanisation, with many opportunities to improve energy use efficiency in multiple ways (such as in India and China). The result was contrary to previous findings from industrialized countries such as Canada and America (Lariviere and Lafrance, 1999; Ewing and Rong, 2008).

The arguments above indicate that more empirical analyses from different contexts are required in order to be able to generalise our existing knowledge of the effects of urbanisation on energy use. In particular, more empirical studies are needed to shed light on specific ways through which urbanisation affects energy consumption in a region.

To fill the gaps in the existing literature mentioned above and to provide a holistic and up-to-date understanding of the relationship between urbanisation and energy consumption in China, this paper aims to answer the following two research questions: 1) Has the process of urbanisation in China contributed to the growth of energy use in the country? 2) What policy interventions have been made in response to rising energy use in urban China?

3. The impact of urbanisation on energy consumption in China

3.1. Methodology

The research methodology has two interrelated components. Firstly, to answer research question one, a time series regression analysis was conducted to depict the overall quantitative relationship between urbanisation and energy consumption at the national level in China. The role of urbanisation in relation to energy consumption is compared with the roles of industrialisation and economic growth at the national level.

Secondly, to answer research question two, based on the theoretical framework of the impact of urbanisation on energy consumption we suggested above, we identified three key pathways through which the rapid urbanisation process has affected energy consumption in China: 1) urban spatial expansion, through which mass energy is used for constructing urban landscapes, including buildings and infrastructure, and for maintenance of an increasing number of buildings. This also gives rise to a growth in the use of cars and related transport energy consumption; 2) transformation to a motorised society, through which mass energy is consumed in the transport sectors for increasing motorised freight and passenger travel in cities; 3) as shown in Fig. 2, the rising quality of life and energy-intensive lifestyles are coupled with the urbanisation process, which stimulates the use of more appliances and related energy consumption in the residential sector.

In Section 4, each pathway identified above will be discussed separately, with some key state policies that have been implemented to curb the growth of energy consumption in the building, transportation and residential sectors will be discussed with respect to their consequences and effects in corresponding sub-sections.

The data used in this research was collected from two sources: China's official statistical yearbooks and a large-scale household survey conducted by a research group from Peking University. The official yearbooks include: the China Energy Yearbook, the China Construction Statistical Yearbook and the China City Statistical Yearbook. These yearbooks provide detailed data on energy use by different sectors, and changes in population, land use, construction and economic activities at national, province and city levels.

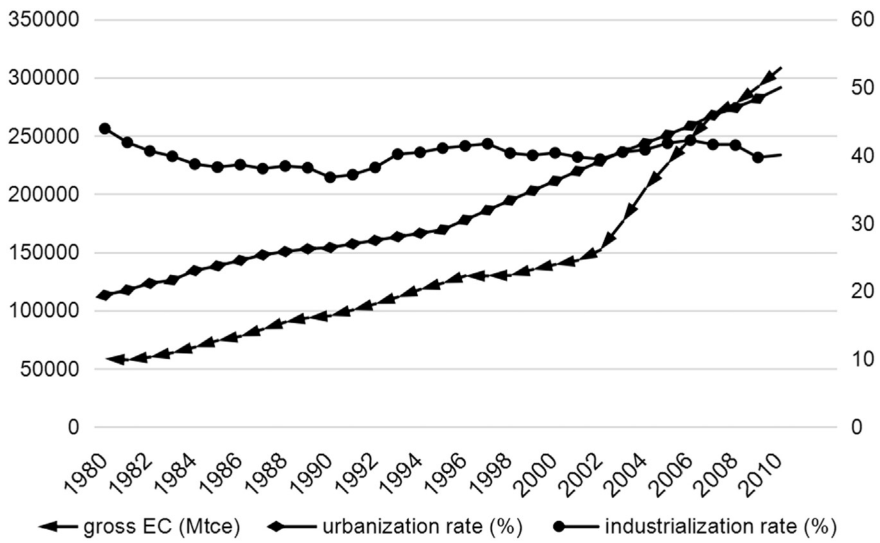

Fig. 2. Changes in gross energy use, urbanisation rate and industrialisation rate in China.
Source: the authors, edited from China Statistical Yearbook, 2010.

Table 1
Review of national energy consumption in China from 1980 to 2010.

Stage	Period	Growth rate (%)	Total energy use (kilotons)	
			1980	2010
Slow growth stage	1980–2002	3.5	56	152
Rapid growth stage	2003–2007	10.9	152	278
Steady growth stage	2008–2010	4.9	278	308

Source: the authors, edited from China Statistical Yearbook, 2010.

The household survey was conducted in 2014 and aimed to collect specific data on energy consumption at a household level and compare household energy consumption between urban and rural households in different climate regions in China. Thirteen Chinese cities from different climate sub-areas were chosen for the surveys. Six of these cities were from northern China and seven from southern China. In each city, two groups of people were investigated: urban residents and rural residents. Sample populations were selected randomly for questionnaires. A total of 826 respondents were interviewed, among which 460 were urban residents and 366 were rural residents. They were asked to report information on factors such as total energy usage, use of appliances and devices, travel behaviour, socioeconomic factors and energy-saving awareness. It should be noted that a non-probability sampling method was used to choose the respondents for the surveys in each city. Therefore, there might be some limitations in our samples.

3.2. Overall relationship between energy use and urbanisation

Table 1 and Fig. 2 show the growth in China's national energy consumption since the 1980s. Generally, energy consumption in China during this period can be divided into three distinct stages. The first stage was from 1980 to 2002, during which the country experienced a tripling of primary energy consumption from 56 to 152 kt of standard coal, with a considerable growth rate of 3.5% annually. During the second stage (2003–2007), China's energy use had unprecedented rapid annual growth of 10.9%. Since 2008, when the Beijing Olympics were held, the total amount of energy used has continued growing, but the average annual growth rate has dropped to 4.9%. One major reason for this drop was the global financial crisis and China's economic recession.

Although the speed of growth has thus decreased, it should be remembered that the absolute amount of energy used has continued to increase. In 2010, China overtook the US, becoming the world's largest energy consumer. Fig. 2 shows that the growth of energy consumption in China was consistent with the rise in the urban population during the period 1980–2010. Conversely, the level of industrialisation, which is measured by the industry value added to GDP, has remained at a relatively stable level, or even continuously decreased since 2006. These results suggest that increasing urbanisation is a major factor related to the growth of energy use.

To examine the effects of urbanisation on energy consumption at a national level in greater detail, a time-series regression analysis was conducted with annual gross energy consumption as the dependent variable. As shown in Table 2, and consistent with previous literature and the theoretical framework suggested above, we assumed that three interrelated aspects of the process of urbanisation could significantly affect energy consumption at the national level: the growth of the urban population, economic development and industrialisation. In the modeling, the urban population growth was indicated by the rate of urban population with respect to total population; economic development was indicated by the annual GDP value; and the industrialisation level was indicated by the percent of annual industrial value added to total annual GDP. To improve the model and estimates, we carefully studied the assumptions of the variables and transformed the quantity of energy consumption and GDP values into logarithms. Table 3 presents the regression results for the natural logarithm of annual national energy use. The adjusted R2 value for the model was 0.979, meaning that 97.9% of the variation in annual energy consumption could be explained by the two significant variables in the model.

The regression analysis in Table 3 shows a similar result as that displayed in Fig. 2. Urban population growth is a major contributor to energy growth in China. The regression results showed that when there was a 1% increase in the urban population, national annual energy consumption grew by 1.4% during the period from 1980 to 2010. Economic development also shows a significant relationship with national energy consumption. The regression results show that when there was a 1% increase in annual gross GDP, energy consumption at a national level increased by 14.5% during the period from 1980 to 2010. However, the regression

Table 2
Variables used in model.

Variable	Index	Date source
Dependent variable		
Energy consumption	The log value of annual gross energy consumption	China Energy Statistical Yearbook, 2011
Explanatory variable		
Urban population growth	The percent of urban population in total population	China Statistical Yearbook, 2011
Economic development	The log value of annual gross GDP	
Industrialisation rate	Percent of industrial value added to total GDP	

Table 3
Results of regression analysis for energy use.

Variable	B	Standard error	t *statistics*	Sig.
Constant	4.397	0.160	27.513	0.000
Urbanisation rate	0.014***	0.002	5.957	1.021
Industrialisation rate	− 1.015	0.004	0.000	0.000
Gross GDP	0.145***	0.037	3.943	0.001
Model summary: $N = 30$, $R = 0.991$, adjust R(Al-mulali et al., 2012) = 0.979				

*** Is significant at $p < 0.01$ level.

results showed there was no significant relationship between the rate of industrialisation and energy growth in China in the same period.

4. Three pathways and policy interventions

4.1. Urban spatial expansion and energy consumption

Urban spatial expansion is a key method by which urbanisation affects energy use. During the period from 1980 to 2010, the built-up area of cities grew five-fold, increasing from 7438 km^2 to 40,058 km^2 between 1980 and 2010 (CSB 1980, 2010). Such rapid urban expansion caused a massive increase in energy use in several ways. Firstly, the rapid growth of the urban population resulted in huge demand for the construction of housing and buildings, roads and other infrastructure, thus increasing energy use. The total floor area of buildings increased from 4485 million km^2 to 25,185 million km^2 during the short period from 1995 to 2010 (China Statistical Bureau, 2011a, 2011b, 2011c, 2011d). Consequently, building energy consumption in China has almost quadrupled since 1995, rising from 1335 mtce to 5197 mtce by 2010 (China Statistical Bureau, 2011a, 2011b, 2011c, 2011d).

In order to respond to rapidly growing energy use in building projects, many policy interventions were undertaken by central and local governments. In particular, attention was paid to the improvement of building materials and energy-saving technologies, and improvements in energy management on construction fields. A series of national standards and codes for building design have also been developed since the 2000s in order to save energy and encourage the use of new green energy (Li and Yao, 2009).

For example, a nationwide Green Building Label Programme (GBL) was introduced in 2008 (Ye et al., 2013). This was the first time China proposed a comprehensive and official green building evaluation system. GBL evaluates green buildings or green communities in terms of 32 applicable technologies for energy saving, renewable energy use and many management rules promoting green construction (Ye et al., 2013). During the period from 2008 to 2011, a total of 353 GBL labels had been issued to individual buildings and communities. The Ministry of Housing and Urban-Rural Development officially certified the buildings and communities with the energy-saving label.

Green-labelled buildings and communities can receive subsidies from the central government. As a result, the total floor area of GBL buildings reached 35 million m^2 by 2012. In addition, energy-efficient codes and standards were implemented across the country (Table 4). These new codes and standards cover many aspects of building construction, such as insulation, sun-shade and ventilation design. As a result, the energy efficiency of construction has improved over this period. Although total building energy consumption increased with the increase in floor area, energy consumption per square metre of construction has shown a significant decrease (50%) since 1995 (Fig. 3). The structure of energy use has also changed, with the proportion of electricity use in buildings increasing from 32.32% to 47.47%, while the use of coal, which was the predominant energy resource in China, decreased from 24.32% to 9.99%.

Secondly, urban sprawl has accelerated energy consumption in China's cities. Urban sprawl became the dominant pattern of urban growth in China's cities from the 1990s (Wang and Zhang, 2010). Urban sprawl is characterised by scattered and low-diversity urban development with low accessibility to public facilities on the urban fringe (Zhao, 2011; Zhao, 2013; Zhao et al., 2009). During the

Table 4
Some energy-efficient building codes and standards in China after 2000.

Code and standard	Field	Year	Target
• Technical specification for energy conservation of existing residential buildings, JGJ 129-2000.	Heating	2000	Existing buildings
• Design standards for energy efficiency of residential buildings in the hot summer and cold winter zones, JGJ 75-2003.	Comprehensive	2003	New buildings
• Standard for energy efficiency inspection of heating systems in residential buildings, JGJ 132-2001.	Heating	2001	New buildings
• Code for design of heating, ventilation and air-conditioning systems, GB50019-2003.	Heating, ventilation and cooling	2003	New buildings
• Technical specification for thermal insulation on external walls of buildings, JGJ144-2004.	Thermal insulation	2004	New buildings
• Standard for lighting design of buildings, GB50034-2004.	Lighting	2004	New buildings

Source: the authors.

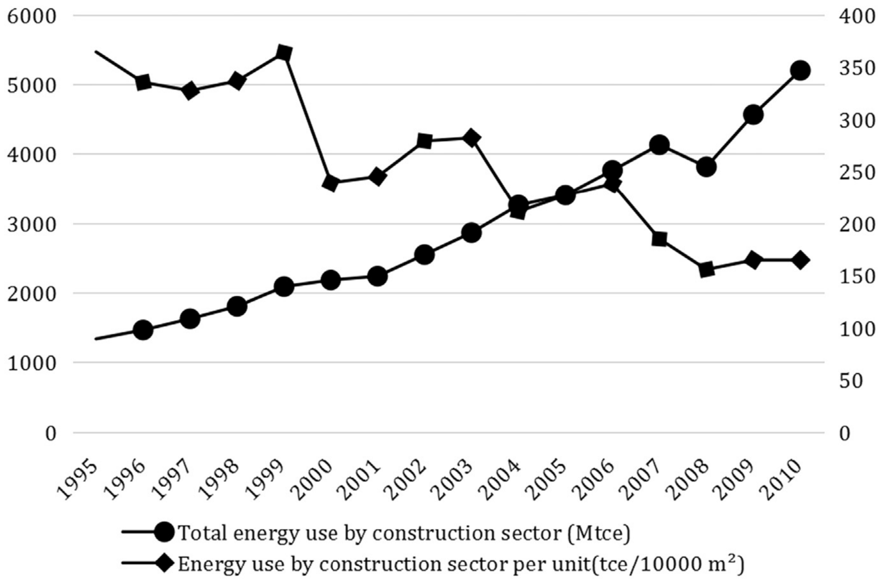

Fig. 3. Changes in construction energy use in China.
Source: the authors, edited from China Energy Statistical Yearbook 2010.

period from 2001 to 2010, urban land use in 15 major cities in China (i.e. cities with a population over 10 million) had increased by 102.1%, while the size of the population in these cities only increased by 52% (CSB 2001, 2010). As a result, the built-up area per capita increased while population density decreased. By 2010, the urban built-up area per capita had reached 101.6m^2 in most cities. The sprawl index (SI) is the built-up area growth as a ratio of population growth. The higher the SI, the higher the level of urban sprawl. Fig. 4 shows the relationship between urban sprawl and energy use per capita from 2001 to 2010. The level of energy consumption per capita had a positive relationship with urban SI. Chongqing, for example, obtained a fairly high SI of 2.74, and the per capita energy consumption of the city increased by 192% during the same period. Hangzhou, which had the lowest SI of 0.61, also had the lowest energy consumption growth rate of 1%. These results show that urban sprawl is a major factor in energy growth.

Urban sprawl has different effects on energy use by different sectors. For example, in Beijing, urban sprawl affects transport energy consumption particularly (Fig. 5) (Zhao, 2010, 2011a; Zhao and Lu, 2011). In Beijing, the built-up area increased by 80% during the period from 1990 to 2010. A huge amount of farmland in the suburbs was transferred into urban use and millions of people chose to live in the suburbs due to lower housing prices or an increase in living space. At the same time, the development of industries and public services was much slower than the rapid growth of housing and population. As a result, many newly developed communities became 'dormitory towns', where residents live but then commute to work in other places. These suburban residents face long commuting distances, with an average of 40 km per day in 2015. Many travel by car, so the travel energy consumption of suburban residents was four times that of their counterparts in the inner city (Zhang and Zhao, 2016).

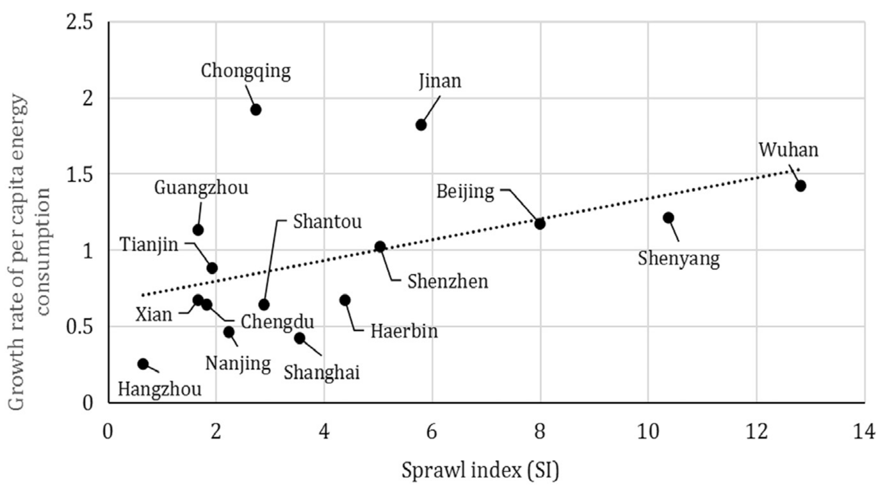

Fig. 4. The relationship between SI and per capita energy consumption.
Source: the authors.

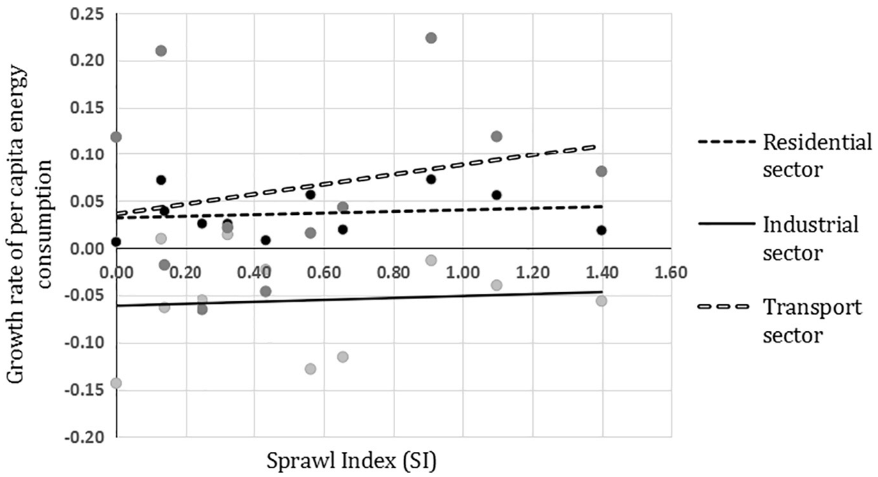

Fig. 5. The relationship between SI and per capita energy consumption by different sector by taking Beijing from 2005 to 2010 as a case.

It is noteworthy that some policy interventions have been implemented to curb the negative effects of urban expansion on energy use. A shift from sprawling growth to compact development and urban regeneration has been encouraged. For example, in 2004, the State Council issued 'further reforms for implementing strict land management', requiring that stricter land management regulations be implemented by local municipal governments to stop urban sprawl. Since then, ministries and local governments have intensively launched various policies to encourage compact development, including high-density development, reuse and redevelopment of old industrial sites, and limits on the proportion of large-sized housing (more than 90 m^2) in real estate development (Table 5). For example, a 'Tripartite Transformation of the Old' policy was launched in Guangdong province. This programme states that the redevelopment of areas of inefficient land use in old villages, old towns and old industrial factories (hence 'tripartite') could meet the area's demand for land for the coming two decades (Yang et al., 2012).

4.2. Urban transportation and energy use

Rapid urbanisation is also characterised by the rapid growth in passenger and freight traffic. During the period from 1980 to 2010, the volume of passenger traffic increased from 230 to 2800 billion people km and the volume of freight traffic increased from 1200 to 14,200 billion tonne km. During the same period, transport energy use increased rapidly: from 1995 to 2010, travel energy consumption increased four-fold, rising from 5864 Mtce to 26,060 Mtce (China Energy Statistical Yearbook 2010). Petrol use for travel rose from 4178 Mtce in 1995 to 21,640 Mtce in 2010. Moreover, GHG emissions from road transport have increased 32-fold since 1980 (Vehicle Pollution Prevention Annual Report 2010, 2010).

The rapid growth in energy use is mainly attributed to an increase in VKT (vehicle kilometres travelled). VKT depends on the travel mode and travel distance. First of all, there was a rapid process of motorisation in urban areas in China. Since 1980, car ownership has increased by 23.5% annually. In 1980, only 2.3 cars were owned per 1000 people; however, this number increased drastically to 58.2 per 1000 by 2010 (China City Statistical Yearbook 2010). Private cars became the dominate travel mode in China's cities. Taking Beijing as an example, the proportion of private car trips increased from 5% in 1986 to 34% in 2010, becoming a primary mode of travel for urban residents. Meanwhile, the proportion of cycling trips dropped substantially from 63% to 16% (Fig. 6). The rapid growth in car travel has been found in other cities, including small and medium-sized cities (Song, 2013). In most

Table 5
Some state policies designed to curb urban sprawl in China since the 1990s.

Policy	Department	Year	Target
• Construction land limit per capita.	MOHURD	1991	Promote urban land use efficiency
• Prime farmland protection system.	The State Council	1998	Protect farmlands from sprawling urban development
• Termination of land provision for villas.	MOLR	2003	Intensity urban land uses
• Reduction of land use quota.	MOLR	2006	Reduce land provision for urban construction uses
• The minimum amount requirement for proportion of small-sized housing (less than 90 m^2) in real estate development.	MOHURD	2006	Promote urban land use efficiency
• Permission system for construction land.	MOLR	2010	Strictly control land provision for urban construction uses

Note: MOHURD is short for Ministry of Housing and Urban-rural Development; MOLR is short for Ministry of Land and Resource.
Source: the authors.

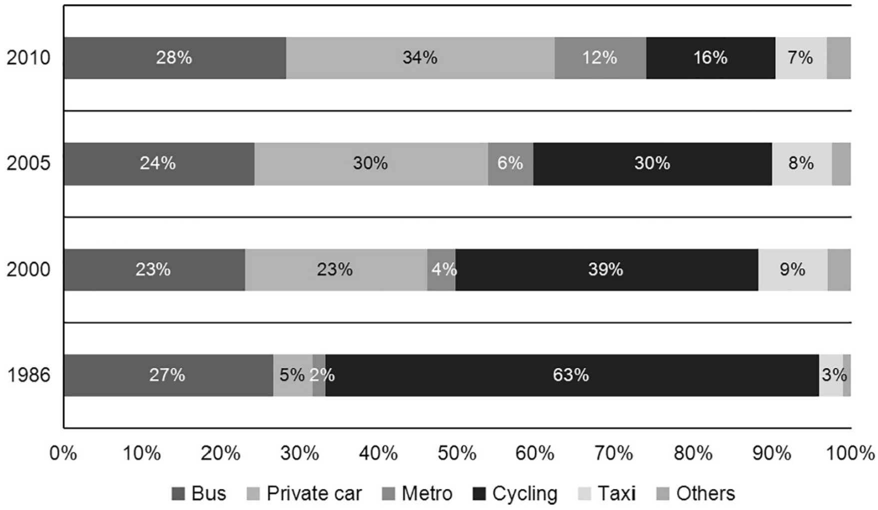

Fig. 6. Changes in residents' travel mode share from 1986 to 2010 in Beijing.
Source: the authors, edited from Beijing Transport Report, 2010.

Chinese cities, private motor travel now accounts for > 30% of total travel.

Travel distance is another factor in VKT. Travel distance has generally increased rapidly in China's cities during the process of urban expansion. For example, in Beijing, the average commuting distance of passengers more than doubled in one decade, rising from 8.4 km in 2005 to 19.2 km in 2015. A similar situation occurred in most large cities across China, such as Shanghai, Guangzhou and Shenzhen. VKT in Shanghai increased from 6.6 km in 1995 to 13.3 km in 2010 (Zhao, 2016). VKT in Guangzhou also increased significantly from 6.1 km in 1998 to 14.8 km in 2010 (Zhao, 2016). Most metropolises had a fairly long VKT, exceeding 10 km by 2010 – for example, Chengdu was 11.5 km, Wuhan 12.6 km, and Nanjing 12.7 km (Zhao, 2016). The rapid growth of VKT has driven the growth of travel energy consumption.

In response to the rapid growth of transport energy use, various policies have been implemented. At the national level, a Transit Metropolis campaign was introduced and the first pilot programme was launched in 13 cities in 2015. According to the policy, the central government grants a huge subsidy to these cities, aiming to improve the public transport system. For example, more transit services and new low-energy buses have been encouraged. In 2016, another national policy was implemented to encourage new energy-efficient cars. According to the policy, if people purchase an electric car or a plug-in hybrid car, they are granted a subsidy between CNY 25000 and CNY 30,000 from the central government. For a new energy bus, the subsidy is between CNY 120,000 and CNY 350,000 (D1EV net, 2017). At the same time, the local municipal governments have also been encouraged to give subsidies for new energy-efficient cars. For example, in Beijing, the subsidy from the municipal government matches that of the central government. In Shenzhen and Shanghai, the city subsidies are even higher than the state subsidy (D1EV net, 2017). The large number of subsidies is one major reason for the increasing proportion of new low-energy cars in China. In addition, in relation to old cars, a new national emissions standard was launched by the central government in 2007. According to the new standard, high-emission cars must be registered in a specific system which is managed directly by the Ministry of Environmental Conservation and are marked with a yellow label. These high-emission cars are also known as ‘yellow label cars’ and are prohibited from driving on roads. However, some of these cars are still used despite being prohibited. Car owners are required to scrap their ‘yellow label cars’ with the help of subsidies from the central government. For example, to scrap one car, the owner could receive a subsidy of between CNY 5000 and CNY 30,000 from the central government in 2015. Given that these old cars are a major source of energy use in the transport sector, the policies dealing with ‘yellow label cars’ might greatly reduce it.

Recently, carpooling has been encouraged in China's cities. In July 2016, China's State Council launched the ‘Interim Provisions for Profit-making Internet-booking Private Carpooling’. For the first time in China, the central government gave legal authorisation to rising private carpooling businesses and companies, including Didi and Uber (Chinese State Council, 2016). Following this, city governments started to introduce new policies to positively regulate the operation of private carpooling, rather than prohibiting it as before. This legalisation promotes the further development of private carpooling in China and is an important incentive to urban residents encouraging them to choose more energy-efficient carpooling as their mode of travel rather than private car travel.

At the city level, many special transport policies have also been implemented. For example, in Beijing, a new lottery system for issuing car licence plates was put into effect in 2011. Only 0.9% of applicants in 2014 obtained car licence plates through this system, the policy effectively limiting the growth of car ownership in Beijing. In 2009, the city suffered from a rapid increase in car ownership, with an annual growth rate of 20%. After the lottery policy was implemented, the growth rate fell to < 6% (Fig. 7). In addition, car usage is restricted in many cities, such as Beijing, Tianjing and Chengdu. For example, cars with a licence plate ending with two given numbers (e.g. 5 and 0, or 4 or 9) are not allowed to be driven in the central urban area in Beijing on week days. This policy reduces daily motor traffic by > 20% and thus saves transport energy.

Inter-city travel is another main source of transport energy use. The amount of travel between cities has been increasing in some

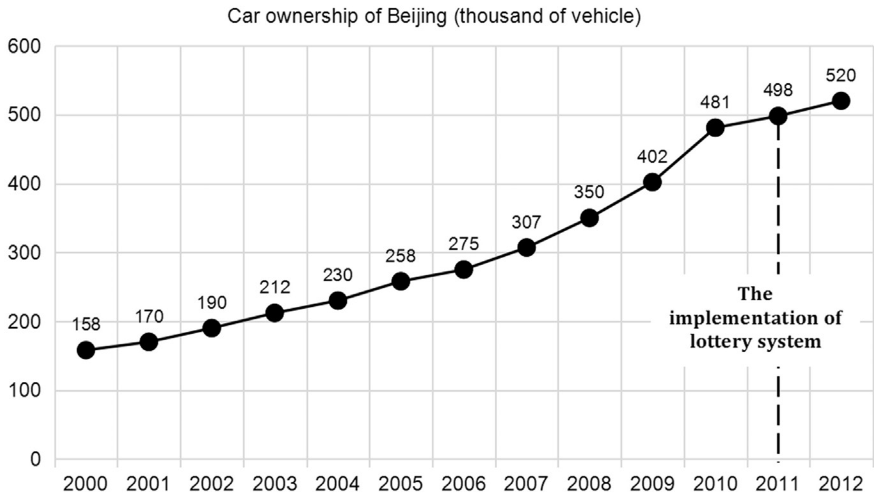

Fig. 7. Car ownership growth before and after the implementation of the lottery system in Beijing.
Source: the authors, edited from Beijing Statistical Yearbook 2009, 2012.

regions, particularly in urban agglomeration areas, such as Jin-jin-ji, the Yangtze River Delta and Pearl River Delta. A high-speed railway system has been built in many areas to improve the accessibility and connection between these cities. The total length of high-speed railways was 22,000 km by the end of 2016. Undoubtedly, the high-speed railway system has the co-benefit of reducing bus and car use by inter-city commuting passengers, and thus reducing the use of petrol. Ben (2013) found that the Beijing-Shanghai high-speed railway reduced road traffic in the Jiangsu Province by > 40%. Qin (2013) estimated that the Nanning-Guangzhou high-speed railway cut road traffic by > 60% in the Guangxi Province.

4.3. Transition in urban lifestyle and residential energy consumption

Total energy use by the residential sector has increased rapidly in China, from 15,745 Mtce to 34,558 Mtce during the period from 1995 to 2010. Per capita residential energy use also doubled over the same period, rising from 130 kgce to 258 kgce (Fig. 8). In terms of consumption of energy, after the industrial sector, the residential sector has become the second largest in China, accounting for over 10% of total energy consumption (China Energy Statistical Yearbook 2010). In particular, the growth of residential energy consumption accelerated significantly after 2004. One of the major reasons for this is the rising quality of life and lifestyle changes.

People's lifestyles have been changing since the 1990s in China, and this trend has become more obvious in the context of rapid urbanisation after the 2000s (Feng et al., 2011; He et al., 2010). This is because millions of rural people migrated to cities and towns, and thus now lead an urban lifestyle. Urban households consume more energy than rural households. Residential energy use by urban

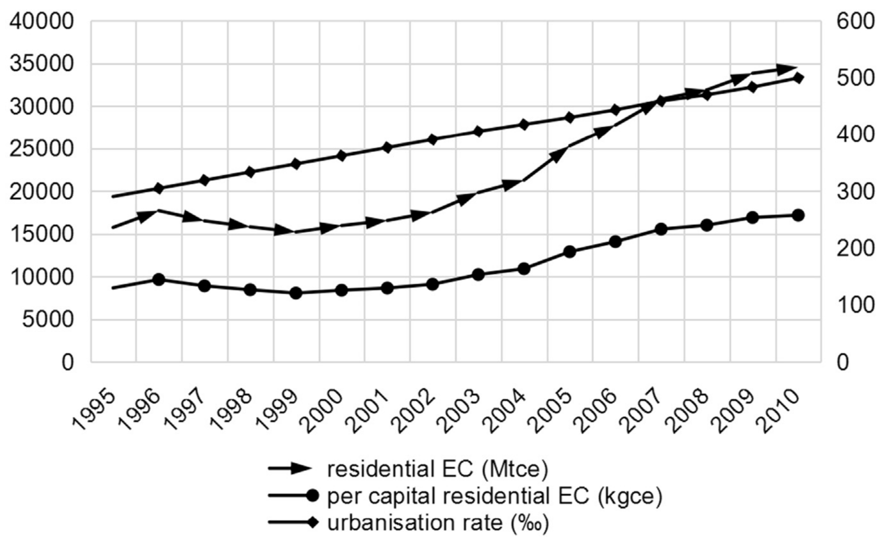

Fig. 8. Changes in residential energy use and per capita residential energy use in China.
Source: the authors, edited from China Energy Yearbook 2010.

Table 6
The difference in annual energy use between urban and rural household sectors in 2010 (by kWh per household).

Sector	Urban	Rural	Difference
• Heating (North).	711.0	701.4	9.6
• Heating (South).	423.4	625.4	− 201.9
• Cooling (North).	321.1	335.5	− 14.4
• Cooling (South).	868.3	726.4	141.9
• Lighting.	250.4	147.4	103.1
• Household appliances.	1469.4	776.5	692.9

Source: Zhao, 2016.

residents accounted for > 70% of total residential energy use in 2011, and their energy use per capita was almost 50% higher than rural residents (China Energy Statistical Yearbook 2012). Table 6 illustrates the urban-rural differences in household energy use for lighting, heating, cooling and other household appliances in China (Zhao, 2016). Urban households across China consumed more energy for lighting and household appliances, while in the north they consumed more energy for heating and in the south more energy for cooling.

Changes in lifestyle in urban areas also affect residential energy use. Urban residents wish to pursue a better life, for example they prefer more spacious housing, own a car, and seek more entertainment and recreation. Between 1980 and 2010, housing floor area per capita increased from 7.2 m^2 to 31.6 m^2 in cities. Meanwhile, living expenditure per capita in urban households also rose. In 2010, it had multiplied by 33 compared to 1980 (China Statistical Bureau 2010). Improvements in people's quality of life have greatly increase residential energy use. For example, in Beijing, house area per capita increased from 4.79 m^2 to 29.4 m^2 between 1980 and 2010. Meanwhile, residential energy consumption per capita grew in step with the housing floor area, increasing from 158.19 to 661.80 kgce (Table 7).

The growing use of household appliances, such as heating and cooling systems, ventilation, lighting and energy for other household tasks, also contributed to growing energy use. During the period from 1995 to 2010, ownership of air conditioners rose rapidly from 0.34 to 112.07 for every 1000 urban households (Table 8). Similar trends also occurred in relation to the ownership of other appliances, including televisions, lamps, refrigerators, heaters and microwave ovens (Table 8). Before 1990, computers were seldom seen in households, but are now a common device in Chinese households. There were 10.37 computers owned for every 1000 urban households in 2012.

The transition to urban lifestyles has not only affected total residential energy use but has also changed the structure of energy use in China. While more efficient and clean energy resources were used for residential energy supplies, electricity took over the role of domestic coal use, becoming the dominant energy resource. By 2010, the proportion of electricity in residential energy consumption had reached almost 60%, while it was only 25.8% in 1995 (Fig. 9). In addition, the proportion of natural gas also showed rapid growth, increasing from 1.5% to almost 8% in 2010. Moreover, although coal remains the predominant primary energy source in the residential sector, the use of coal has become more efficient. Before 1990, almost 90% of residential energy in China came from the direct burning of coal (Feng, Lin & Zhao, 2011). This has now changed, with 60% of the coal used for household energy converted into electricity rather than direct burning in 2010 (Feng, Lin & Zhao, 2011).

5. Discussion and policy implications

Many previous studies have argued that urbanisation is a vital factor influencing energy consumption in a country or region (Jones, 1989; Lariviere and Lafrance, 1999; Ewing and Rong, 2008; Poumanyvong et al., 2012; Malenbaum, 1978). Looking at China as a case study, the paper contributes fresh evidence to the field. The results of the analyses show that urbanisation is significantly related to the amount and structure of energy use. During the rapid urbanisation process from 1980 to 2010, for every 1% increase in the urban population ratio, energy consumption rose by 1.4%. When total annual GDP increased by 1%, energy consumption increased by 14.5%. In China, urbanisation increased energy use in three main ways: urban spatial expansion, which increases energy

Table 7
Changes in housing floor area and residential energy use in Beijing.

Year	Average housing floor area (m^2/per capita)	Average residential energy use (kgce/per capita)
1980	4.79	158.19
1985	6.15	286.24
1990	7.72	339.41
1995	9.03	361.15
2000	11.15	391.24
2005	18.81	537.41
2010	29.4	661.8

Source: the authors, edited from China Energy Yearbook 2010.

Table 8
The changes in ownership of household appliances in urban China from 1990 to 2010.

Household appliance	1990	2000	2010
• Air conditioner.	0.34	30.80	112.07
• Refrigerator.	42.33	90.10	96.61
• Microwave oven.	NA	17.60	59.00
• Heater.	868.3	49.10	84.82
• Colour television.	59.40	116.60	137.43
• Computer.	NA	9.70	71.16

Unit: the number in every 1000 households.
Source: China Statistical Bureau 1990, 2000, 2010.

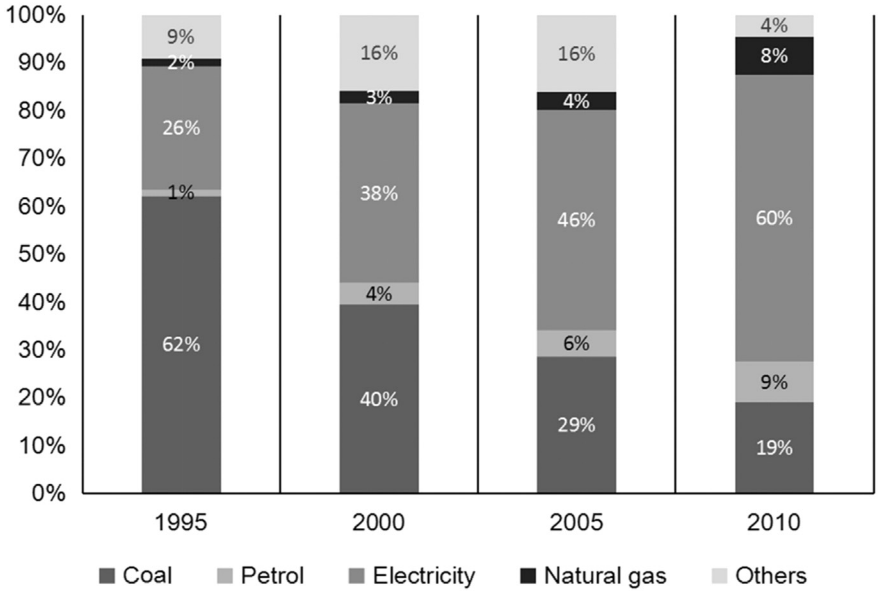

Fig. 9. Changes in the structure of residential energy consumption in China.
Source: the authors, edited from China Energy Yearbook 2010.

use in new buildings and introduces urban sprawl; urban motorisation, which increases energy-intensive transportation; and the rising quality of life and growth of energy-intensive lifestyles.

The results of the above analysis demonstrate that policy interventions in both energy supply and demand could play an important role in building an energy-efficient society in China. Since the 1990s, most of China's cities have transitioned from compact to sprawling cities (Zhao, 2011). This urban sprawl has caused scattered, low-density and low-diversity suburbs, meaning that urban policies designed to encourage compact urban growth could play a vital role in saving energy. Policies which enhance compactness, density and diversity of cities should be considered closely, especially the notion of urban growth boundaries (UGB), which are currently being discussed by the state and municipal governments.

Such changes are often easy to point to in theory but difficult to implement in practice. Anti-sprawl policies face challenges when being implemented in China's cities (Zhao, 2013), as state and municipal growth controls on urban sprawl may not be achieved by all local jurisdictions when local economic motivations are involved. This might be the case when urban sprawl has been fuelled by the development of urban real estate, which can create significant revenue for local government and private developers. Such situations seem to be compounded by a trend towards local autonomy and fiscal responsibility in the current decentralisation process.

The above analyses show that transport policies and building-standards requirements could play an important role in reducing energy use. Both regulations and fiscal policies should be implemented to encourage bus use and active transport modes (walking and cycling), while restricting private motor travel. In addition to licence limits, more policies should be applied in this area; for example, Beijing has been considering applying a congestion fee to restrict motor travel. Additionally, comprehensive energy-efficient codes and standards should be enacted to promote the construction of energy-efficient buildings.

Many previous studies have found that individual environmental awareness and energy-efficient behaviour in residents are important for energy saving in cities (Lindén et al., 2006; Poortinga et al., 2004); however, despite being discussed in the academic field (Crompton and Wu, 2005; Liu and Diamond, 2005), urban residents in China still have a low level of environmental awareness (Harris, 2006). The results of the above analyses show that a change of lifestyle in the city, in the context of social transition, has had a vital impact on energy consumption in China.

Such issues should be addressed further, as the growing consumer society now accommodated by China's cities is a major factor in the rapid increase in residential energy use. The transition from a producer society to a consumer society occurred in China during the rapid urbanisation process (Tse et al., 1989). Due to economic growth, residents of cities possess much more wealth and disposable income than before. Per capita disposable income increased 45.5 times between 1980 and 2010, rising from CNY 411 to CNY 19,109 (China Statistical Bureau 2010). A consumer society has been established where residents consume much more, not only to meet rising standards of basic living, but also for leisure, entertainment and other purposes.

The impact of consumer-driven society is being strengthened by the growth of the middle class in China, which accounted for 109 million in 2010, making up 7.9% of the total population. Their daily basic expenditure was between USD 10 and USD 20, in terms of purchasing power parity (Chen and Qin, 2014). The middle class prefer living in large-sized housing, purchasing single-family detached houses, driving high-emission vehicles and adopting other energy-intensive lifestyle features. These consumption habits and luxury lifestyles have gone far beyond the aim of raising the quality of life for all, and have become a display of wealth, marking them as middle class. In particular, they use more high-emission SUV and luxury cars, which have consistently gained in popularity in China, and are now the fastest-growing choice of car.

The growth of the e-Society is another important aspect of China's urbanisation process in recent years. China has the largest online e-market in the world and e-commerce has become the fastest-growing industry in China during the last decade. The gross merchandise volume (GMV) of e-commerce in China reached CNY 16.4 trillion in 2015, with an annual growth rate of 20% during the period 2008 to 2015 (CSB, 2015). In particular, the GMV of online shopping was CNY 3.5 trillion in 2015, accounting for 23% of e-commerce GMV (iResearch, 2015). In China's big cities and developed areas, online shopping has become a major form of shopping for urban residents: it is estimated that over 350 million people in China have experienced online shopping. The number of users of Taobao, the largest online shopping website in China, exceeded 800 million by 2012 (Taobao 2013). Conversely, online shopping has remained at a low level in undeveloped small towns, especially in rural areas where internet services are limited. However, this situation has also been changing recently, due to the development of internet connections and telecommunications in rural areas. Where online shopping grew quickly in undeveloped urban areas, it changed consumption culture and promoted an energy-intensive lifestyle, even in small towns and rural areas.

6. Conclusion

Cities have become a major battlefield in humankind's struggle to save energy and combat climate change and air pollution across the world. The link between urbanisation and energy use has been increasingly attracting the attention of researchers and politicians. China is now the largest energy consumer and greenhouse gas emitter in the context of ongoing rapid urbanisation. This paper explored how China's rapid urbanisation process affected energy use during the period from 1980 to 2010. The results of the analyses showed that urbanisation is significantly related to the amount and structure of energy use. After industrialisation, urbanisation is the second largest phenomenon to have a profound effect on energy consumption. Urbanisation has increased energy use in three main ways: urban spatial expansion, which increases energy use from new buildings and introduces urban sprawl; urban motorisation, which includes energy-intensive transportation; and a rising quality of life and growth in energy-intensive lifestyles. Urbanisation also affects the structure of energy use, with petrol and electricity replacing the local use of coal to become the major energy sources in most cities.

Policy interventions to change the features and elements of urbanisation could play an important role in saving energy. They include, for example, a more sustainable urban structure and an increase in energy efficiency in the industrial, building and transport sectors. In particular, urban growth management could reduce energy use by curbing urban sprawl, encouraging compact development and promoting public transport. When developing future policies, more attention should be paid to individual energy use behaviour and environmental awareness. A growing consumption-driven society, with an energy-intensive lifestyle, is becoming common. In China, in particular, the growth of the middle class has driven the rise in luxury and energy-intensive lifestyles, including the use of high-emission cars and the building of large-sized, single-family detached houses. The rapid growth of online shopping and the emerging e-Society is also increasing consumption levels in small towns and undeveloped rural areas. In addition to all of these changes, China is now facing a new era, with an aging society. The elderly are expected to account for > 15% of the total population by 2030. All of these social and economic transitions are bringing new challenges to energy saving policies in China within the context of ongoing rapid urbanisation.

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